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Sexual dimorphism of the metacarpals in contemporary Cretans: Are there differences with mainland Greeks?

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Abstract

Sex in the adult skeleton can usually be reliably determined through an assessment of features found on the pelvis and cranium. In the lack of these elements it is necessary to elaborate other methods to establish sex in skeletonised remains recovered in forensic cases. Standards for other bones (e.g. humerus, metacarpals and metatarsals) have already been established for the Greek population. The aim of this study is to determine whether the standards for metacarpals provided from a study on the Athens collection are representative of a modern Cretan population.

Using a digital caliper we took 7 measurements on each one of the left and right metacarpal bones of 108 adult individuals from a modern collection from Crete. Totally twenty formulae for left and right bones created from the Athens collection were used to sex the sample of this study.

The overall classification accuracy obtained for our sample was very close to the cross-validated accuracy reported by the authors. However, looking at the classification accuracy for males and females, a consistent trend for low classification rates in females was observed. New formulae were developed for the Cretan sample yielding up to 85% classification accuracy.

This study clearly indicates that the standards for metacarpals developed from the Athens collection are not appropriate for application in forensic cases for the island of Crete as they do not represent the local population efficiently. This may hold true for other regions of Greece thus great caution should be taken when applying these standards. Obviously more research is needed to confirm these results.

Key words: Forensic Anthropology, Metacarpals, Sex estimation, Crete, Greece

Introduction

When identifying human remains in a forensic or archaeological setting, estimation of sex is unquestionably the primary task. Sexing a complete skeleton can be a fairly easy process however this is rarely the case in forensic settings [1]. Scavenging and severe fragmentation can seriously impede reliable sex estimation. Single fragments and small bones can be recovered far away from the crime/death scene and often they are not associated with the rest of the body. Such circumstances highlight the importance to have multiple alternative methods for sex estimation using different skeletal elements. Metacarpals [e.g. 2], metatarsals [e.g. 3] phalanges [4], patella [5] and vertebrae [6] have been studied and proven to be useful in that aspect. Herein we are particularly interested in metric standards developed from the metacarpals.

Scheuer and Elkington [2] developed a sex estimation method based on six measurements for each metacarpal (MTC); interarticular length, mediolateral width of the base, anteroposterior width of the base, mediolateral width of the head, anteroposterior width of the head, and maximum midshaft diameter. Their study was conducted on a contemporary British sample of 60 individuals and resulted in sex allocation rates between 74% and 94%, with MTC I being the best predictor. Ever since, the method was tested [7] and modified [4, 8] by several authors.

Falsetti [4] verified the existence of sexual dimorphism in metacarpals by applying a modification of the previous method in a sample from the Terry collection. Interestingly he found significant differences only in metacarpals II, IV and V with accuracy rates ranging between 84.37% (MTC V), and 92.0% (MTC II). After validation with two independent samples he concluded that the formulae may be used to identify metacarpals of unknown population affinity.

Stojanowski [9] used a sample from the University of Mexico (n=80) to generate 35 linear discriminant functions for metacarpals, seven for each bone. Accuracies ranged between 75% and 90% for the validation sample with metacarpal IV being the most successful. A later study by Burrows et al. [10] tested the methods of Scheuer and Elkington [2], Falsetti [4], and Stojanowski [9] using a sample of 23 modern Americans. Stojanowski's [9] approach performed best compared to the other two in the aforementioned study [10]. Similarly Barrio et al. [7] used 79 individuals from a modern Spanish sample achieving accuracies up to 91% accuracy (for the left metacarpal II).

Studies on the sexual dimorphism were also become popular in Asia. In 2012, Khanpetch and colleagues [8] developed metric standards for sex estimation from metacarpals based on a modern population from Chang Mai, Thailand. The authors used binary logistic regression and receiver operating characteristics (ROC) analysis to create equations for sex estimation from each metacarpal for both left and right side. According to their results the best sex indicator for the left side was MTC II (89.8%) and for the right side MTC V (89.3%).

Lazenby [11] tested bilateral asymmetry on the second metacarpals on a sample of 19th Century Canadians and found significant differences between left and right bones. The right metacarpal II provided the highest accuracy in males, exceeding 90%. Smith [12] also found significant changes between right and left bones, however the left metacarpals performed better in this study. A paper on the hand length of a Nigerian population also reports bilateral asymmetry [13].

In a recent study, Manolis et al. [14] applied seven dimensions, previously defined by others [1, 4, 12] to a Greek population (n=151) from the Athens Collection. Accuracies ranged between 79.6%-88.9% for the left, and 80.2%-88.9% for the right metacarpals, with the highest discriminations found in the left metacarpal I, and the right metacarpal V.

It is obvious that the previous studies differ greatly in their findings without any apparent logic (sometimes MTC II is the best sex indicator for the left side and MTC V is the best sex indicator for the right side), which may be simply reflecting a sample effect rather than population differences. The goal of this study is to test the equations developed by Manolis et al., [14] for the Greek population using a sample from the Cretan collection. So far there are no studies looking at the expression of skeletal sex dimorphism between different regions of Greece. Cretans are habitants of an island mostly occupied in rural activities while the Athens sample is a mixed population deriving most probably from many different regions of Greece. There is a scope in testing whether the standards provided by the previous study can be applicable in Crete.

Material and methods

A total of 814 metacarpals from 108 skeletons (51 males and 47 females) were employed in this study. The skeletons belong to the Cretan collection, a modern osteological collection housed at the Department of Forensic Sciences of the University of Crete [15]. Seven measurements were following Manolis et al. [14] as defined by Scheuer and Elkington [2], Falsetti [4], and Smith [12]. The measurements were taken with a digital sliding caliper (Mitutoyo).

Bilateral assymetries were tested using student's t-test. A one-way ANOVA was carried out to explore differences between the two sexes ($p<0.05$). Sexual dimorphic index (SDI) was calculated following Ricklan and Tobias [16].

Stepwise discriminant function analysis was used (Method: Wilk's lambda with F=3.84 to enter and F=2.71 to remove) to select the combination of variables that best discriminate males and females. Several combinations of selected variables were subjected to direct discriminant function analysis to develop sex estimation formulae for the metacarpals. Univariate discriminant function analysis was also carried out for all measurements.

A standard leave-one-out classification procedure was applied, in order to compare the accuracy rate of the original sample and the one created by cross-validation. This procedure classifies all individual bones, by applying to each one of them the functions derived from all samples with the exception of one. The closest the cross-validated accuracy to the original accuracy the more reliable is the method. Data analysis was carried out using the discriminant function subroutines of SPSS 19.0

Results

a) Bilateral asymmetries

Table 1 shows the results of the paired student's T-test. According to these results there are no differences between the mean values of left and right first metacarpal variables at $p<0.05$ (Except MLMD). Therefore we decided to use the mean values of the measurements for developing the standards for metacarpal I. However right metacarpals II-V demonstrate consistent higher mean values for all measurements (with the exception of APDDE for MTC II and ML for MTC V). These differences are statistically significant at the level of $p< 0.05$. This contradicts the results on Manolis et al., [14] who found no statistically significant differences between left and right mean values in their sample. For metacarpals II-V separate equations for left and right bones were developed.

b)One way ANOVA and sexual dimorphic index (SDI).

Descriptive statistics of 7 measurements and the associated univariate F-ratio to measure the differences between the sexes are shown in **Table 2**. For metacarpal I we found no significant differences between right and left thus we used the mean values for comparison between males and females. For the rest of the bones we analysed separately left and right bones. The differences between the means in males and females were significant ($p<0.001$) for all measurements in all cases. Sexual Dimorphic Index was calculated for every variable and ranged from 5.37 to 14.33. MLDM and APDM have shown consistently high values while ML showed consistently low values in all metacarpals.

b) Efficiency of the Athens standards for the Cretan sample

We tested all the formulae proposed by Manolis et al., [14] which were developed for a mixed population from Athens (ATH). The results are summarised in **Table 3**. According to our calculations the ATH formulae seem to classify the Cretan sample reasonably well if compared with the cross-validated results and the test sample in Manolis's paper. However once the accuracy is broken down in male and female groups it becomes evident that Cretan females are misclassified as male in very high percentages. For instance Formulae 1 for the Metacarpal I when applied to the Cretans classifies correctly 73.6% of the total sample which is reasonably close to the overall 86.2% reported by the authors; however it classifies correctly 35/36 males (97,6%) and only 18/36 females (50%). The same pattern is repeated for F2 for MTC1 where the classification accuracy for females does not exceed 9% (3/36). It is evident that the formulae developed from the Athens collection are not appropriate for the Cretan sample which is more representative of the actual Cretan population. Thus it is important to develop separate standards for sex estimation for the given population.

d)Univariate discriminant functions

Table 4 demonstrates the demarking points and the classification accuracy for single dimensions. For example, a maximum length of left MTC II smaller than 66 mm is assigned as female while a length greater than that is assigned as male. The most effective single dimension, as demonstrated by direct discriminant analysis for MTC I, were MLDM and APDM (77.6%), for left MTC II was MLDPE (85.3)% for left MTC III was APDPE (78.7%) etc. The best univariate equation was based on the left MTC II (85.3%) followed by the right metacarpal IV (81.5%). Note that demarking values for metacarpal I are calculated from the mean values of the specimens while for metacarpals II-V separate univariate equations were developed for right and left bones. Univariate equations with less than 70% overall accuracy were omitted from Table 4 as they are of limited value for forensic applications.

e) Multivariate discriminant functions

Multivariate discriminant functions and classification accuracy for left and right metacarpals in modern Cretans are presented in **Table 5**. The best equation for MTC I yielded 84% classification accuracy using the mean values of three variables (MLDM, APDM and MLDPE). The best left bone for sex estimation was MTC II and the best multivariate equation used three variables: the mediolateral diameter of the proximal (MLDPE), the distal (MLDDE) end and the midshaft (MLDM). The best right bone for sex estimation was MTC IV and the best multivariate equation (F18) used three variables: The maximum length (MLM) the mediolateral diameter of the distal end (MLDDE) and the anterior-posterior diameter of the midshaft (APDM).

g)Posterior Probabilities

Posterior probabilities of each individual were also calculated for the best multivariate equations, since they reflect the affinity of each case to be reassigned to the original group. Fig. 1 demonstrates the probability levels of correct group assessment according to the discriminant scores of each individual for the 6 best formulae (F3, F7, F15, F18, F21 and F25) as seen in Table 5. For example, if a discriminant score based on Function 25 for Right MTC IV measurements is -2.2 (x coordinate), the posterior probability of that individual coming from a female group is 98 % (y coordinate).

Sex estimation congruence

It would be interesting to explore sex estimation congruence by looking at the consistency in sex estimation between the different bones. Our sample however consists of skeletons that in many cases are missing some metacarpal bones. Seventeen skeletons of our sample had all 5 left metacarpals and thus it was possible to see the consistency in sex estimation by looking at the results for Manolis et al. and our F1 formula for each left metacarpal. A summary table of the results can be found in the supplementary material (Supplementary table 1). This small sample indicates consistency in sex estimation between the different bones but a larger sample is needed in order to verify this hypothesis.

Discussion

Forensic anthropology casework often includes mutilated and /or fragmentary skeletal remains or even single elements. The investigation of skeletal remains on the island of Crete, Greece has yielded about 29 cases with potential forensic relevance in the past 10 years. Of these 11 emerged in 2013-2014 (Source: Department of Forensic Sciences, University of Crete and Division of Forensic Pathology in Crete, Ministry of

Justice) and six (55.6%) concerned single skeletal elements (e.g. cranial fragments, long bones) making the existence of methods for biological profiling a vital step in the forensic investigation.

Greece has a significant bulk of skeletal studies to present the last 10 years. Since the foundation of the first modern reference collection in Athens [17] and the Cretan collection at the University of Crete, numerous research papers dealing with standards on modern Greeks have emerged. Studies on skull [15] pelvis [18], long bones [e.g. 19, 20] and other bones [21] have verified the existence of sexual dimorphism for the Greek population. However no study so far tested the efficacy of the skeletal standards to truly represent different populations in Greece. The Athens collection is based on cemetery remains of people from all over Greece [17] while the Cretan collection was predominantly assembled from individuals that were born and died on the island. Are the standards from Athens representative of the Cretans? If so, the methods developed in this collection can be directly applicable on the emerging forensic cases on the island. In the opposite case though, the application of these methods would be problematic.

We measured left and right metacarpal bones of 108 individuals from the Cretan collection and performed a student's T-test to explore the existence of bilateral asymmetries. We detected statistically significant differences ($p<0.05$) between right and left bones for the vast majority of measurements. These results are in agreement with previous studies on metacarpals [11,12] and hands [13]. This however contradicts the results for the Athens sample for which the authors report no statistical significance between left and right side [14]. Most studies, including ours, report predominantly higher mean values for the measurements of the right bones compared to the left [11, 12, 14], yet; there is no agreement on which side is more effective sex indicator.

The primary aim of this study was to test the sex estimation method developed for the metacarpals based on the Athens collection [14]. Totally twenty formulae for left and right bones were used to sex the sample (N=108) of this study. The results at first glance appeared promising since in most cases the overall classification accuracy obtained for our sample was very close to the cross-validated accuracy reported by the authors [14]. However looking at the classification accuracy for males and females, one could observe a consistent trend for low classification rates in females that in some cases did not exceed 9% (Table 3). The males on the other hand were classified in higher rates compared to the reported accuracies for the Athens sample [14]. Similar results were obtained by Lazenby [11] when he tested the Scheuer and Erlinghton [2] equations on a 19th Century Canadian sample. These results reinforce the conclusions of Khanpetch et al [8] according to which balanced allocation accuracy for both sexes is more important than a higher overall sex allocation accuracy in forensic situations. The low classification rate in females in our study means that upon application of the method in Cretans there is a high possibility that females would be identified as males which naturally would impede accurate identification of unknown skeletal remains.

To assure that appropriate standards are available for the Cretan sample a new set of univariate and multivariate discriminant functions was developed in the second phase of this study. The classification results did not exceed 81% for univariate and 86% multivariate predictive models. The best left bone for sex estimation was MTC II and the best multivariate equation used three variables: the mediolateral diameter of the proximal (MLDPE), the distal (MLDDE) end and the midshaft (MLDM). The best right bone for sex estimation was MTC IV and the best multivariate equation used three variables: the maximum length (MLM) the mediolateral diameter of the distal end (MLDDE) and the anterior-posterior diameter of the midshaft (APDM). The accuracy rates seem to be lower compared to other studies [2, 4, 7, 8, 14]. This may indicate a smaller degree of sexual dimorphism on the Cretan population that could be associated with rural activities of female increasing the robusticity of the hand bones.

Another interesting observation from our analysis is the fact that length is found to be a significant contributing factor in sex estimation for this population which agrees with earlier reports on long bones from the Cretan collection [e.g. 19-20] but again contrasts the Athens [14].

The high misclassification rates for the Cretan females, the report of bilateral asymmetry in Cretans and the relative differences in the mean values reported for the two samples indicates that significant differences do exist between the two samples. Is there an evident biological difference between the Cretans and the rest of the Greeks? Or this simply means that the samples we tested assuming they are representative of two populations (mainland Greeks and islander Cretans) are simply failing to depict all variability of the populations? There is no evidence to support either statement. The relatively small sample sizes for some bones are also a restrictive factor when it comes to the statistical analysis. However a fact remains that if the Athens standards are not appropriate for the Cretans they may as well not be for other regions of Greece. This needs to be tested and verified in order to suggest the application of these methods to forensic settings. Especially for the metacarpals perhaps the merging of the two samples can result in a more representative pool of data for the population of Greece as a whole.

Conclusions:

Sexual dimorphism of the metacarpals is well established in the literature and standards for the Greeks have been proposed. However there is no data on whether the Cretan population is satisfactorily represented in the Athens sample. A test of the methods developed for the Athens sample results in high misclassification rates for the females in addition to the existence of bilateral asymmetry contrary to the original study. There is no evidence to support whether these results indicate a significant biological difference between mainland Greeks and Cretans or is just a difference between the samples. This must be further explored by testing other skeletal elements. This study suggests that the Athens standards are not appropriate for the Cretans and proposes new population specific standards for the metacarpals that can be directly applicable to forensic casework in the island of Crete.

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Figure 1: Posterior probabilities of correct group assessment according to the discriminant scores of each individual for the 6 best formulae (F3, F7, F15, F18, F21 and F25) developed for the Cretan sample.

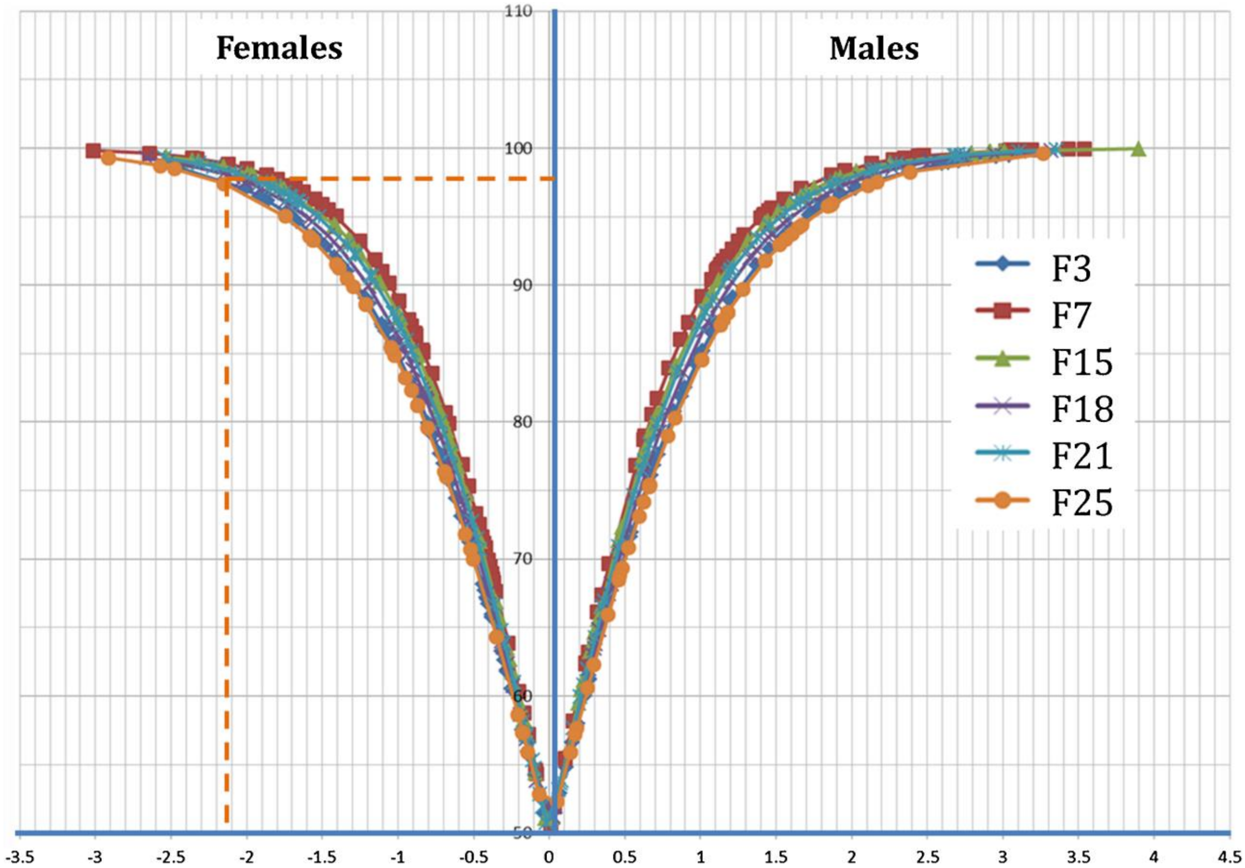

Table 1: Bilateral asymmetries for all measurements in metacarpals from the Cretan population.

			MTC1 (N=36)		MTC2 (N=69)		MTC3 (N=60)		MTC4 (N=48)		MTC5 (N=31)	
ML	L	MEAN	44.41	t=-1.11	66.61	***t=-2.41**	65.17	t=-1.7	55.29	t=-1.18	**51.94**	t=0.44
		SD	3.246		4.534		4.147		3.722		3.830	
	R	MEAN	44.60		66.93		65.46		55.42		51.85	
		SD	3.053		4.644		4.414		3.751		3.657	
MLDDE	L	MEAN	15.69	t=-1.24	14.94	***t=-4.61**	14.42	***t=-4.98**	12.32	***t=-4.18**	12.18	***t=-2.79**
		SD	1.356		1.105		1.209		1.078		0.902	
	R	MEAN	15.85		15.27		14.84		12.60		12.49	
		SD	1.571		1.194		1.337		0.967		0.935	
APDDE	L	MEAN	13.33	t=1.07	**14.54**	t=-1.7	14.06	***t=-2.25**	12.24	***t=-3.39**	11.57	t=-1.69
		SD	1.384		1.229		1.129		0.916		1.074	
	R	MEAN	13.16		14.32		14.32		12.58		11.83	
		SD	1.369		1.404		1.393		0.993		0.744	
MLMD	L	MEAN	11.59	***t=-3.44**	8.20	***t=-3.09**	8.15	***t=-2.41**	6.36	***t=-2.47**	7.27	***t=-2.69**
		SD	1.180		0.851		0.719		0.862		0.735	
	R	MEAN	11.89		8.57		8.29		6.53		7.57	
		SD	1.290		1.416		0.762		0.786		0.916	
APDM	L	MEAN	8.24	t=-0.43	8.82	***t=-5.64**	8.94	***t=-8.33**	7.11	***t=-4.93**	6.60	***t=-4.63**
		SD	0.881		0.997		0.807		0.801		0.705	
	R	MEAN	8.29		9.23		9.46		7.37		7.08	
		SD	0.933		0.996		0.959		0.764		0.780	
MLDPE	L	MEAN	15.57	t=-0.58	18.19	t=-0.035	13.91	***t=-2.98**	11.80	t=-0.26	13.52	t=-0.64
		SD	1.174		1.686		1.279		1.067		0.901	
	R	MEAN	15.65		18.20		14.30		11.82		13.60	
		SD	1.207		1.534		1.452		1.247		0.882	
APDPE	L	MEAN	**15.73**	t=0.93	16.14	***t=-4.7**	16.43	***t=-2.83**	12.19	***t=-4.57**	11.29	t=-0.02
		SD	1.428		1.406		1.323		1.259		1.159	
	R	MEAN	15.56		16.66		16.75		12.71		11.28	
		SD	1.431		1.437		1.300		1.335		1.199	

*p<0.01, Bold values indicate a higher mean value for the left side measurements

Table 2. Means, Standard deviations and F-ratios and SDI for all the variables of left and right metacarpals in modern Cretans.

		Metacarpal II						Metacarpal III					
Left		Males (*N* = 59)		Females (*N* = 43)		*F*-VALUE	SDI	Males (*N* = 52)		Females (*N* = 48)		*F*-VALUE	SDI
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
	MLM	68.3	3.86	63.74	3.51	36.32	6.68	67.11	3.62	62.1	2.82	54.44	7.46
	MLDDEM	15.52	1.01	14.02	0.91	58.34	9.64	14.96	1.03	13.56	1.02	43.39	9.36
	APDDEM	14.97	1.01	13.79	1.05	32	7.84	14.61	1.11	13.38	0.71	39	8.43
	MLDMM	8.54	0.75	7.57	0.54	51.94	11.38	8.36	0.63	7.66	0.57	31.72	8.41
	APDMM	9.21	0.87	8.26	0.68	35.76	10.34	9.34	0.78	8.39	0.53	46.73	10.23
	MLDPEM	18.99	1.31	16.79	1.04	83.07	11.59	14.45	1.11	13.05	0.81	46.87	9.66
	APDPEM	16.74	1.36	15.41	1.19	26.46	7.97	17.02	1.17	15.36	0.86	59.86	9.8
Right		Males (*N* = 60)		Females (*N* = 48)		*F*-VALUE	SDI	Males (*N* = 59)		Females (*N* = 43)		*F*-VALUE	SDI
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
	MLM	68.35	4.02	64.15	3.56	32.15	6.14	67.52	3.92	62.25	3.69	46.79	7.81
	MLDDEM	15.61	1.08	14.37	1.13	33.33	7.9	15.35	1.18	13.87	1.02	44.47	9.66
	APDDEM	14.78	1.18	13.57	1.01	32.1	8.23	14.92	1.46	13.5	1.13	29.09	9.54
	MLDMM	8.89	1.44	7.9	0.63	19.59	11.11	8.57	0.64	7.96	1.52	6.99	7.15
	APDMM	9.51	0.86	8.69	0.83	24.9	8.61	9.87	0.89	8.77	0.62	49.47	11.09
	MLDPEM	18.89	1.45	17.2	1.04	46.29	8.95	14.73	1.4	13.5	1.01	24.56	8.35
	APDPEM	17.18	1.25	15.77	1.23	34.65	8.23	17.26	1.2	15.75	1.03	44.1	8.74
Left		Metacarpal IV						Metacarpal V					
		Males (*N* = 46)		Females (*N* = 40)		*F*-VALUE	SDI	Males (*N* = 39)		Females (*N* = 27)		*F*-VALUE	SDI
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
	MLM	57.17	3.29	52.97	2.94	38.11	7.34	53.9	3.07	50.15	2.63	26.03	6.96
	MLDDEM	13.04	0.85	11.72	0.94	45.96	10.12	12.53	0.93	11.6	0.85	16.94	7.45
	APDDEM	12.88	0.87	11.72	0.68	45.38	9	12	0.79	11.15	1	14.24	7.08
	MLDMM	6.82	0.79	6	0.52	31.54	12.09	7.55	0.73	6.88	0.69	14.33	8.99
	APDMM	7.66	0.67	6.63	0.53	60.73	13.48	7	0.57	6.37	0.8	14.11	9.05
	MLDPEM	12.43	0.98	11.24	0.92	33.17	9.62	14.1	1.1	12.89	0.77	24.58	8.6
	APDPEM	12.95	1.15	11.57	0.94	36.53	10.71	11.61	0.96	10.66	1.12	13.6	8.2
Right		Males (*N* = 40)		Females (*N* = 41)		*F*-VALUE	SDI	Males (*N* = 40)		Females (*N* = 41)		*F*-VALUE	SDI
		Mean	SD	Mean	SD			Mean	SD	Mean	SD		
	MLM	57.33	3.37	53.59	2.96	27.9	6.53	53.12	3.28	50.27	2.59	13.65	5.37
	MLDDEM	13.14	0.8	12	0.82	39.68	8.68	12.7	0.81	11.92	0.85	12.81	6.11
	APDDEM	13.21	0.8	12.06	0.77	42.81	8.69	12.17	0.75	11.45	0.73	13.75	5.87
	MLDMM	6.96	0.61	6.08	0.61	41.7	12.65	7.87	1.02	7.25	0.77	7.22	7.88
	APDMM	7.99	0.68	7.02	0.47	57.05	12.2	7.41	0.71	6.82	0.66	11.31	8
	MLDPEM	12.5	1.14	11.34	1.11	21.55	9.29	13.97	0.84	13.15	0.82	14.38	5.89
	APDPEM	13.34	1	12.18	1.07	24.89	8.64	11.97	0.95	10.7	0.93	27.14	10.63

		METACARPAL I					
Mean		Males (*N* = 58)		Females (*N* = 49)		*F*-VALUE	SDI
		Mean	SD	Mean	SD		
	MLM	46.34	3.96	42.78	2.4	30.13	7.68
	MLDDEM	16.52	1.56	15.12	1.12	27.51	8.49
	APDDEM	14.06	1.36	12.63	0.98	37.96	10.19
	MLDMM	12.49	1.26	10.83	0.87	61.17	13.31
	APDMM	8.97	0.98	7.78	0.66	52.14	13.21
	MLDPEM	16.31	0.97	14.97	0.99	48.71	8.16
	APDPEM	16.27	1.45	15.33	1.49	10.81	5.77

Table 3. Classification accuracy of the Cretan sample using all four equations developed from the Athens collection for left and right metacarpals.

	F1			F2			F3			F4		
	N	%	ATH	N	%	ATH	N	%	ATH	N	%	ATH
MTC1L												
TOTAL	53/72	73.6	86.2	39/72	54.2		49/72	68.1		54/72	75.0	
MALES	35/36	97.2	85.4	36/36	100	75.6	35/36	97.2	85.4	28/36	77.8	88.9
FEMALES	18/36	**50.0**	87.2	3/36	**8.3**		14/36	**38.9**		26/36	72.2	
MTC2L												
TOTAL	81/100	81.0	82.3	73/100	73.0		80/100	80.1		69/100	69.0	
MALES	54/59	91.5	78.5	47/59	79.7	73	55/59	93.2	86	44/59	74.6	83.3
FEMALES	27/41	**65.9**	87.5	26/41	63.4		25/41	61.1		25/41	61.0	
MTC3L												
TOTAL	71/93	76.3	83.8	61/93	65.6		56/93	60.2		66/93	71.0	
MALES	50/51	98	84.4	49/51	96.1	74.8	35/51	68.6	83.8	46/51	90.2	86.5
FEMALES	21/42	**50**	83.0	12/42	**28.6**		21/42	**50.0**		20/42	**47.6**	
MTC4L												
TOTAL	70/84	83.3	87.1	62/84	73.8		68/84	81.0		59/84	70.2	
MALES	42/45	93.3	89.8	34/45	75.6	73.8	38/45	84.4	87.4	30/45	66.7	87.1
FEMALES	28/39	71.8	83.3	28/39	71.8		30/39	76.9		29/39	74.4	
MTC5L												
TOTAL	49/65	75.4	80.6	49/65	75.4		51/65	78.5		50/65	76.9	
MALES	32/39	82.1	81.5	31/39	79.5	75.8	35/39	89.7	79.6	33/39	84.6	80.8
FEMALES	17/26	65.4	79.5	18/26	69.2		16/26	**59.3**		17/26	65.4	
MTC1R												
TOTAL	56/70	80.1	86.3	52/7	74.3		51/70	72.9		59/70	84.3	
MALES	38/41	92.7	87.2	35/4	85.4	84.3	37/41	90.2	85.9	32/41	78.1	85.4
FEMALES	18/29	62.1	85.4	17/29	**58.6**		14/29	**48.3**		27/29	93.1	

MTC2R												
TOTAL	78/109	71.6	80.8	74/109	67.9		75/109	68.8		89/109	81.7	
MALES	59/61	96.7	80.0	47/61	77.1	72.3	59/61	96.7	84.8	57/61	93.4	80.2
FEMALES	29/48	**60.4**	81.81	27/48	**56.3**		26/48	**54.2**		32/48	66.7	
MTC3R												
TOTAL	65/99	65.7	85.1	60/99	60.6		66/99	66.7		75/99	75.8	
MALES	51/52	98.1	83.92	46/52	88.5	78.2	50/52	96.2	87.1	42/52	80.8	83.3
FEMALES	14/47	**29.8**	86.66	14/47	**29.8**		16/47	**34.0**		33/47	70.2	
MTC4R												
TOTAL	55/81	62.2	84.7	56/81	69.1		53/81	65.4		66/81	81.5	
MALES	41/42	97.6	85.2	28/42	66.7	76.0	41/42	97.6	88.9	29/42	69.1	81.6
FEMALES	14/39	**35.9**	84.1	28/39	71.8		12/39	**30.8**		37/39	94.9	
MTC5R												
TOTAL	42/58	72.4	83.9	37/58	63.8		39/58	67.2		43/58	74.1	
MALES	25/28	89.3	85.1	18/28	69.2	79.8	26/28	92.9	85.1	24/28	85.7	84.3
FEMALES	17/30	**56.7**	82.5	19/30	63.3		13/30	**43.3**		19/30	63.3	

Table 4: Univariate statistics, cut-off values and classification accuracy for the measurements for right and left metacarpals.

				Original					Cross validated classification				
				Males		Females		Total	Males		Females		Total
MTC I				N	%	N	%	%	N	%	N	%	%
	MLM	Mean	F<44.56<M	42/58	72.4	36/49	73.5	72.9	42/58	72.4	36/49	73.5	72.9
	MLDDE	Mean	F<15.81<M	45/58	77.6	37/49	75.5	76.6	45/58	77.6	37/49	75.5	76.6
	APDDE	Mean	F<13.34<M	45/58	77.6	37/49	75.5	76.6	44/58	75.9	37/49	75.5	75.7
	MLDM	Mean	F<11.66<M	42/58	72.4	42/49	85.7	78.5	42/58	72.4	41/49	83.7	77.6
	APDM	Mean	F<8.47<M	43/58	74.1	42/49	85.7	79.4	42/58	72.4	41/49	83.7	77.6
	MLDPE	Mean	F<15.64<M	45/57	78.9	36/49	73.5	76.4	45/57	78.9	36/49	73.5	76.4
MTC II	MLM	L	F<66.01<M	44/59	74.6	29/41	70.7	73.0	44/59	74.6	29/41	70.7	73.0
	MLDDE	L	F<14.77<M	44/59	74.6	32/42	76.2	75.2	44/59	74.6	32/42	76.2	75.2
		R	F<14.98<M	48/60	80.0	28/48	58.3	70.4	48/60	80.0	28/48	58.3	70.4
	APDDE	L	F<14.38<M	43/59	72.9	31/42	73.8	73.3	43/59	72.9	31/42	73.8	73.3

		R	F<14.17<M	38/60	63.3	38/48	79.2	70.4	38/60	63.3	38/48	79.2	70.4
	MLDM	L	F<8.05<M	44/59	74.6	33/43	76.7	75.5	44/59	74.6	33/43	76.7	75.5
		R	F<8.39<M	43/60	71.7	39/48	81.3	75.9	41/60	68.3	39/48	81.3	74.1
	APDM	L	F<8.73<M	41/59	69.4	36/43	83.7	75.5	41/59	69.5	36/43	83.7	75.5
	MLDPE	L	F<17.89<M	47/59	79.7	40/43	93.0	85.3	47/59	79.7	40/43	93.0	85.3
		R	F<18.04<M	37/60	61.7	40/48	83.3	71.3	37/60	61.7	40/48	83.3	71.3
	APDPE	L	F<16.07<M	41/59	69.5	31/43	72.0	70.6	41/59	69.5	31/43	72.0	70.6
		R	F<16.47<M	44/60	73.3	36/48	75.0	74.1	44/60	73.3	36/48	75.0	74.1
MTC III	MLM	L	F<64.61<M	38/51	74.5	34/43	79.1	76.6	38/51	74.5	34/43	79.1	76.6
		R	F<64.9<M	41/51	80.4	34/47	72.3	76.5	41/51	80.4	34/47	72.3	76.5
	MLDDE	L	F<14.26<M	37/52	71.1	31/42	73.8	72.3	36/52	69.2	31/42	73.8	71.3
		R	F<14.61<M	40/51	78.4	36/48	75	76.8	40/51	78.4	36/48	75	76.8
	APDDE	L	F<13.99<M	34/52	65.4	33/42	78.6	71.3	34/52	65.4	33/42	78.6	71.3
		R	F<14.21<M	34/51	66.7	41/48	85.4	75.8	34/51	66.7	41/48	85.4	75.8
	MLDM	L	F<8.01<M	39/52	75	30/43	69.8	72.6	39/52	75	30/43	69.8	72.6
	APDM	L	F<8.86<M	36/52	69.2	33/43	76.7	72.6	36/52	69.2	33/43	76.7	72.6
		R	F<9.32<M	33/51	64.7	40/48	83.3	73.7	33/51	64.7	40/48	83.3	73.7
	MLDPE	L	F<13.75<M	38/51	74.5	34/43	79.1	76.6	38/51	74.5	34/43	79.1	76.6
	APDPE	L	F<16.19<M	39/51	76.5	36/43	83.7	79.8	39/51	76.5	35/43	81.4	78.7
		R	F<16.5<M	39/51	76.5	36/47	76.6	76.5	39/51	76.5	36/47	76.6	76.5
MTC IV	MLM	L	F<55.07<M	33/45	73.3	30/40	75.0	74.1	33/45	73.3	30/40	75.0	74.1
		R	F<55.46<M	29/40	72.5	28/40	70.0	71.3	29/40	72.5	28/40	70.0	71.3
	MLDDE	L	F<12.37<M	35/46	76.1	31/39	79.5	77.6	34/46	73.9	31/39	79.5	76.5
		R	F<12.56<M	31/40	77.5	29/40	72.5	75.0	31/40	77.5	29/40	72.5	75.0
	APDDE	L	F<12.29<M	34/46	73.9	33/39	84.6	78.8	33/46	71.7	33/39	84.6	77.6
		R	F<12.63<M	33/40	82.5	29/40	72.5	77.5	33/40	82.5	29/40	72.5	77.5
	MLDM	L	F<6.40<M	32/46	69.6	30/40	75.0	72.1	31/46	67.4	30/40	75.0	70.9
		R	F<6.52<M	32/40	80.0	33/41	80.5	80.2	31/40	77.5	33/41	80.5	79.0
	APDM	L	F<7.14<M	34/46	73.9	33/40	82.5	77.9	34/46	73.9	32/40	80.0	76.7
		R	F<7.50<M	31/40	77.5	35/41	85.4	81.5	31/40	77.5	35/41	85.4	81.5
	MLDPE	L	F<11.83<M	32/45	71.1	29/40	72.5	71.8	32/45	71.1	29/40	72.5	71.8
		R	F<11.91<M	31/40	77.5	30/41	73.2	75.3	31/40	77.5	30/41	73.2	75.3
	APDPE	L	F<12.25<M	33/45	73.3	29/40	72.5	72.9	33/45	73.3	29/40	72.5	72.9
		R	F<12.76<M	30/40	75.0	27/41	65.9	70.4	30/40	75.0	27/41	65.9	70.4
MTC V	MLM	L	F<52.02<M	29/39	74.4	20/26	76.9	75.4	29/39	74.4	20/26	76.9	75.4
	MLDDE	L	F<12.06<M	27/39	69.2	19/26	73.1	70.8	27/39	69.2	19/26	73.1	70.8
		R	F<11.80<M	22/28	78.6	19/31	61.3	69.5	22/28	78.6	19/31	61.3	70.0
	MLDM	L	F<7.21<M	29/39	74.4	17/27	63	69.7	29/39	74.4	17/27	63	70.0
		R	F<7.56<M	19/28	67.9	23/32	71.9	70	19/28	67.9	23/32	71.9	70.0
	APDM	L	F<6.68<M	27/39	69.2	19/27	70.4	69.7	27/39	69.2	19/27	70.4	70.0
	MLDPE	L	F<13.49<M	26/39	66.7	20/27	74.1	69.7	26/39	66.7	20/27	74.1	70.0
		R	F<13.55<M	20/28	71.4	21/31	67.7	69.5	20/28	71.4	21/31	67.7	70.0
	APDPE	L	F<11.13<M	26/39	66.7	21/27	77.8	71.2	26/39	66.7	21/27	77.8	71.2
		R	F<11.33<M	20/28	71.4	27/31	87.1	79.7	20/28	71.4	27/31	87.1	79.7

Table 5. Multivariate Discriminant functions and classification accuracy for left and right metacarpals in modern Cretans

										Original					Cross validated				
										MALES		FEMALES		TOTAL	MALES		FEMALES		TOTAL
MTC I	MEAN	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F1	0.097	-0.155	0.209	0.395	0.266	0.581	-0.277	-16.182	43/57	75.4	42/49	85.7	80.2	41/57	71.9	42/49	85.7	78.3
	F2				0.629		0.464		-14.606	43/57	75.4	41/49	83.7	79.2	43/57	75.4	41/49	83.7	79.2
	F3				0.452	0.366	0.400		-14.590	46/57	80.7	43/49	87.8	84.0	46/57	80.7	43/49	87.8	84.0
	F4				0.594	0.532			-11.382	44/58	75.9	44/49	89.8	82.2	40/58	69.0	44/49	89.8	78.5
MTC II	LEFT	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F5	0.094	0.424	-0.088	0.377	0.024	0.437	-0.052	-21.478	47/59	79.7	37/41	90	84	46/59	78	37/41	90.2	83
	F6	0.099	0.448				0.476		-21.675	48/59	81.4	37/41	90	85	47/59	80	36/41	87.8	83
	F7		0.363		0.475		0.517		-18.453	48/59	81.4	39/42	93	86.1	47/59	80	39/42	92.9	85.1
	F8				1.072	0.574			-13.644	45/59	76.3	36/43	84	79.4	45/59	76	34/43	79.1	77.5
	RIGHT	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F9	0.065	0.181	0.127	0.195	0.181	0.260	0.118	-18.742	44/60	73.3	40/48	83	77.8	43/60	72	36/48	75	73.1
	F10					0.478	0.611		-15.377	42/60	70	39/48	81	75	41/60	68	39/48	81.3	74.1
	F11			0.214	0.227	0.250	0.370	0.171	-16.692	45/60	75	39/48	81	77.8	44/60	73	38/48	79.2	75.9
	F12				0.486	0.815			-11.501	42/60	70	37/48	77	73.1	40/60	67	37/48	77.1	71.3
MTC III	LEFT	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F13	0.128	0.212	-0.014	-0.146	0.6069	0.206	0.213	-21.592	40/51	78.4	37/42	88	82.8	40/51	78	36/42	85.7	81.7
	F14	0.148				0.6861		0.3427	-21.218	41/51	80.4	38/43	88	84	40/51	78	37/43	86	81.9
	F15	0.125	0.1777	-0.014		0.5616	0.214	0.2054	-21.649	40/51	78.4	38/42	91	83.9	40/51	78	37/42	88.1	82.8
	F16				0.6282	1.0942			-14.687	38/52	73.1	34/43	79	75.8	38/52	73	34/43	79.1	75.8
	RIGHT	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F17	0.117	0.281			0.6216		0.0958	-19.0502	39/51	76.5	40/47	85	80.6	39/51	77	40/47	85.1	80.6
	F18	0.124	0.316			0.6649			-18.8894	41/51	80.4	40/47	85	82.7	41/51	80	40/47	85.1	82.7
MTC IV	LEFT	MLM	MLDDE	APDDE	MLDM	APDM	MLDPE	APDPE	constant	N	%	N	%	%	N	%	N	%	%
	F19	0.095	0.317	0.252	0.063	1.035	0.147	-0.240	-18.856	36/45	80.0	33/39	85	82.1	36/45	80.0	30/39	76.9	78.6
	F20	0.164				1.214			-17.741	35/45	77.8	34/40	85	81.2	34/45	76	34/40	85	80

Supplementary table 1: Results for sex estimation formula (F1) in Manolis' and our study for each left metacarpal.

	sex	Manolis et al. 2009					This study				
		MT1L	MT2L	MT3L	MT4L	MT5L	MT1	MT2L	MT3L	MT4L	MT5L
1	F	c	c	c	c	c	c	c	c	c	c
2	M	c	c	c	c	c	c	c	c	c	c
3	M	c	c	c	c	c	c	c	c	c	c
4	M	c	c	c	c	c	c	c	c	c	c
5	M	c	c	c	c	c	c	c	c	c	c
6	M	c	c	c	c	c	c	c	c	c	c
7	M	c	c	c	c	c	c	c	c	c	c
8	F	c	c	c	c	c	c	c	c	c	c
9	F	w	c	c	c	c	c	c	c	c	c
10	F	c	c	w	c	c	c	c	c	c	c
11	M	c	c	c	c	w	c	c	c	c	w
12	M	c	c	c	c	c	w	c	c	w	w
13	F	w	w	w	c	w	w	c	w	w	w
14	M	c	w	c	c	w	c	w	c	w	w
15	F	w	w	w	w	c	c	c	c	w	c
16	M	w	w	c	w	w	w	w	w	w	w
17	F	w	w	w	w	w	c	w	w	w	c

* c: correct sex assessment,w:wrong sex assessment, MTL1: F1 for left MTC I, MTL2: F1 for left MTC II, MTL3: F1 for left MTC III, MTL4: F1 for left MT IV, MTL5:F1 for left MTC V, MT1: F1 for mean MTC I in our study. Note that F1 is the formula that uses all measurements for each bone (see Results).